# An Investigation of the Influence of Waves on Sediment Processes in Skagit Bay

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## LONG-TERM GOALS

In this work we will employ an unstructured grid, coupled wave-current-sediment model to study the influence of wave-induced near bottom stresses on the sediment transport and morphological change within the Skagit River delta and Skagit Bay in Western Washington. The resulting coupled wave-current model will resolve the influence of external processes, including tidal forcing, buoyant river discharge, fluvial sediment supply and wind on tidal flat sediment transport. It will be used to evaluate the capabilities of state-of-the-art open source sediment models and to examine dynamic processes influencing net sediment transport over tidal flats and channel networks including convergence fronts; tidal asymmetries; buoyancy forcing; spatial and temporal variations in bed stress; and interactions between channel networks and adjacent tidal flats.

## OBJECTIVES

Given the need for a high-resolution model of Skagit Bay that includes fully integrated wave, hydrodynamic, and sediment components, our project is designed to meet the following objectives: couple the existing high-resolution hydro-sediment model of Skagit Bay with a phase-averaged surface wave model, work closely with field measurement programs on the North Fork Flats (S. Elgar and B. Raubenheimer [WHOI]) and South Fork Flats (R. Geyer, P. Traykovski, and D. Ralston [WHOI]) on model-observation comparisons and validation; and use the coupled model to characterize the wave-current regime in Skagit Bay and the spatial distribution of wave-induced bottom shear stresses and their role in the large-scale morphodynamics of the flats.

## APPROACH

The integrated modeling system to be constructed for this project will consist of two primary components, a hydrostatic primitive equation coastal ocean model FVCOM, and an unstructured grid, phase-averaged surface wave model SWAN. We selected these models because of their capability of resolving wave and current dynamics in the coastal regime. FVCOM is a Fortran90 software package for the simulation of ocean processes in coastal regions (Chen et al., 2003,2006). The publicly available model has a growing user base and has been used for a wide variety of applications.

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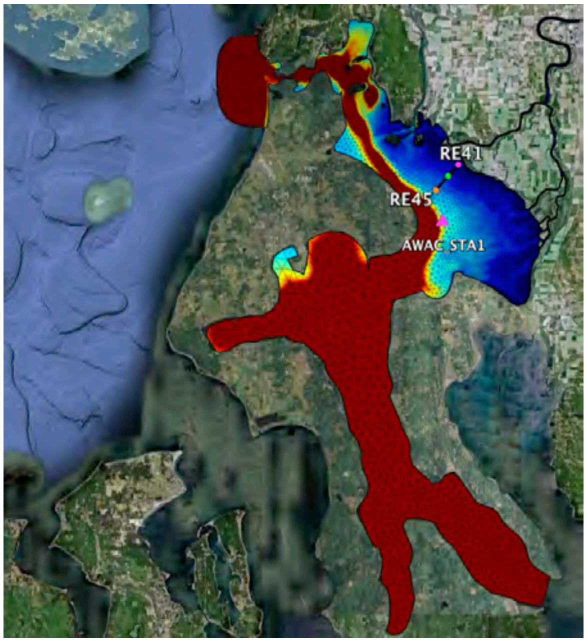
Supported by the Tidal Flats DRI, the model is currently being used to support investigations of Skagit Bay by G. Cowles (UmassD, N00014-08-1-1115), D. Ralston (WHOI), and Jim Lerczak (OSU).




The kernel of the code computes a solution of the hydrostatic primitive equations on unstructured grids using a finite-volume flux formulation. The FVCOM kernel is used to drive a number of attached modules, including the Community Sediment Transport Modeling System (CSTMS, Warner et al, 2008). The surface wave model SWAN is a third generation phase-averaged wave model that was developed specifically for application in coastal waters (Booij et al., 1999). SWAN includes the deep-water source term parameterizations common to most surface wave models, including wave generation by wind, energy dissipation from whitecapping, and quadruplet wave-wave interaction. In an effort to make the model more suitable for the nearshore regime, SWAN also contains important finite-depth parameterizations such as refraction, bottom friction, shoaling, depth-induced breaking and triad wave-wave interactions. For this work, the we use a recently implemented option for unstructured grid spatial discretization of the wave action equation in geographical space was used (Zijlema, 2010).

## WORK COMPLETED

### 1. Personnel
A research associate (Eric Holmes) was supported by the project.

### 2. Model setup
For the coupled wave-current simulations we will employ two models of differening resolutions. Both of these models were developed with support from the ONR Tidal Flats DRI (N00014-08-1-1115). A summary of metrics for these models is included below. The 4.3 model will be used for the majority of the runs as the coupled wave-current model places a very high demand on computational resources.

***Table 1: Specifications of Models for coupled Wave-Current studies of Skagit Bay***

| Model | Elements | Layers | Resolution [Flats/Mean] | Hydrodynamic Time Step (s) | Wave Model Time Step (minutes) |
|---|---|---|---|---|---|
| skg3.16 | 112K | 21 | 20m / 50m | 1 | 15 |
| skg4.3 | 15K | 11 | 100m / 200m | 5 | 15 |

The hydrodynamic model is forced using tides at the Swinomish, Deception, and Sandy Point open boundaries and is forced with fresh river flux and sediment load from the Skagit River. Details of the specific forcing assigned is described in detail in the reporting for grant N00014-08-1-1115 which supported the hydrodynamic model development. Wind forcing for the wave and hydrodynamic

models for realistic experiments will be based on the 10-m wind field derived from hindcasts of the Weather Research and Forecasting model for the Skagit Region (provided by D. Ralston, WHOI). It is expected that these wind fields provide the best representation of the topographically-driven spatial variability in the wind field. The wave model will not be forced at the open boundary as the potential for propagation of waves from the open boundary into Skagit Bay proper is limited.

SWAN and FVCOM are integrated on collocated grids (Fig 1). The domain contains the entirety of Skagit Bay and extends south through Saratoga Passage and west through Deception Pass. This domain was enlarged from that of earlier studies (Yang and Khangaonkar, 2008) in order to reduce the influence of the boundary field and allow for export of sediment from the Bay. The model contains 15K elements with a horizontal discretization of 100m on the Skagit flats. Bathymetry is derived from the Puget Sound DEM, the Fir Island LIDAR dataset, and several datasets collected during the course of the ONR DRI study. FVCOM is driven at the open boundaries by tidal harmonics. Freshwater flux for the Skagit River is derived from the USGS gauge at Mt. Vernon. In the present work, a constant value of Q = 500 m^3/s, representing the climatological mean, is used.

**RESULTS**

**1. Wave Modeling**

Due to complex topography and land-sea surface temperature differences the spatial structure of the wind field is complex and point measurements are not suitable for simulations across the full extent of the domain. In this work, SWAN was forced by surface wind fields constructed using hindcasts of the Weather Research and Forecasting model (WRF) for Skagit Bay (D. Ralston, WHOI). Wave heights for SWAN are set to zero on the open boundary as the swell has limited ability to propagate into the interior of the Bay. Numerical and physics parameters used in SWAN runs are provided in Table 1.

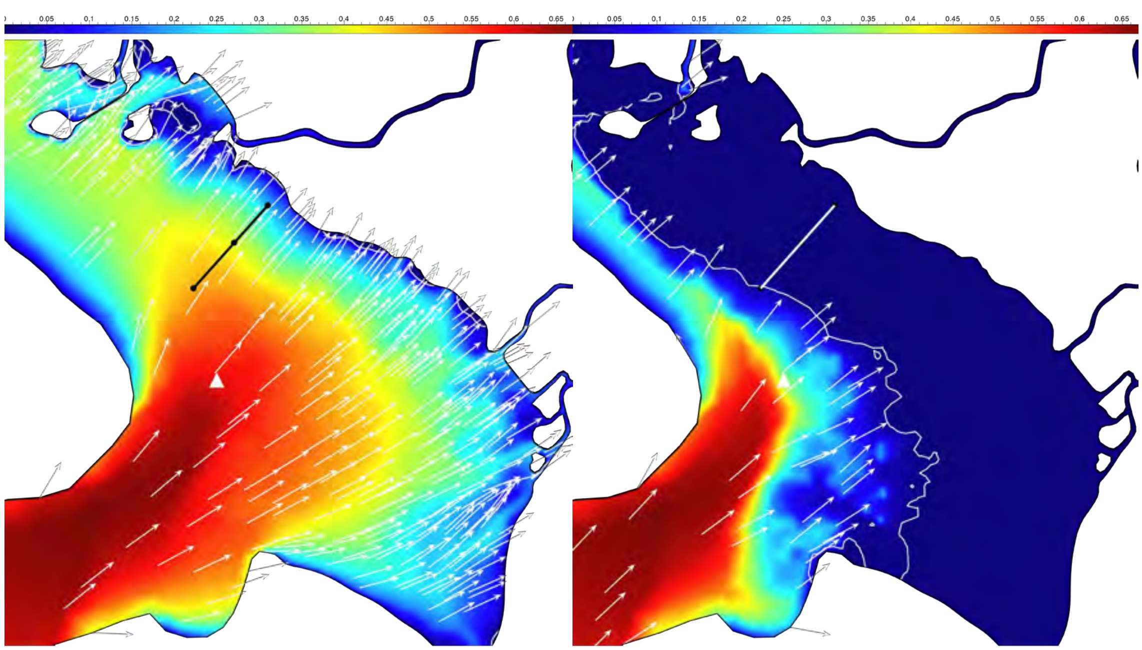


***Fig. 2: Wave direction vectors and significant wave height for a SW wind at 10 m/s during spring high tide (left) and spring low tide (right)***

The model-computed amplitudes compare well with observations (Fig. 3) for several cross-flat sites on flats near the north fork of the Skagit River (RE41-RE45) and a site on the edge of the flats near the south fork of the Skagit River (AWAC Sta1). Dependancy of frequency and energy with depth and fetch also compare well (Fig. 4). The contribution of the waves to the bedstress is greatest on the upper parts of the flats during onshore winds (Fig 5.).

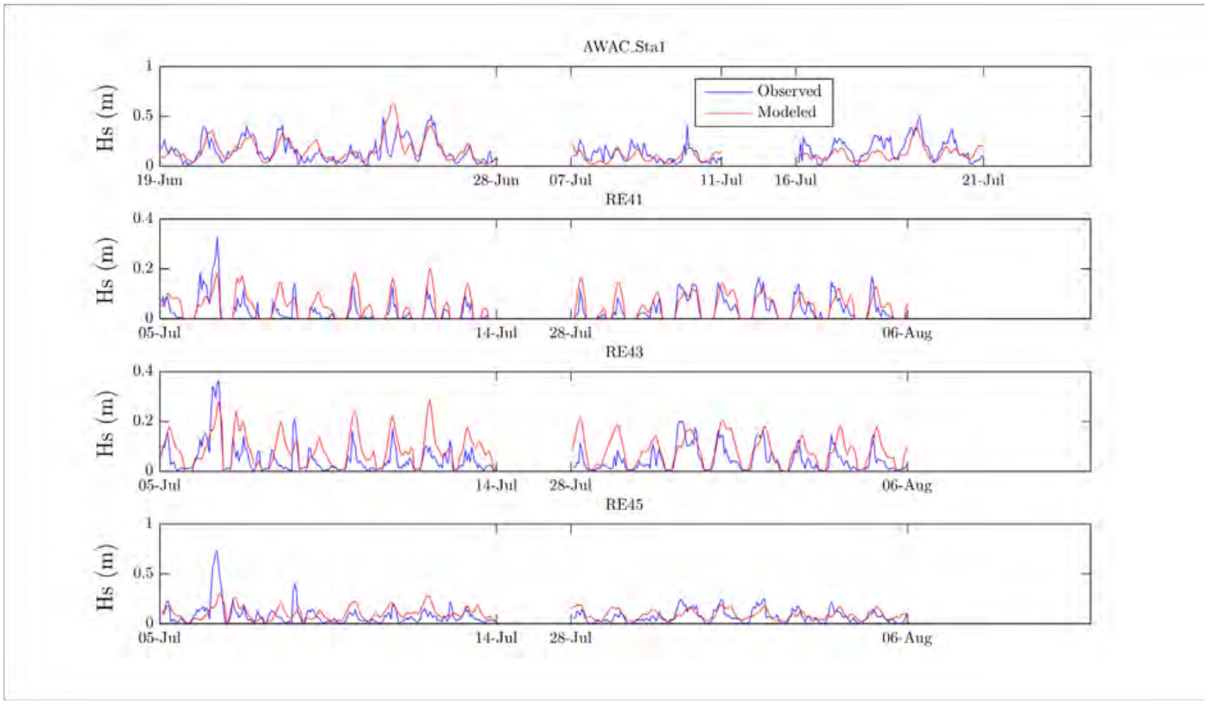



***Fig. 3: Comparison of model-computed and observed significant wave height during several wind events in summer, 2009. For station locations, see Figure 1.***

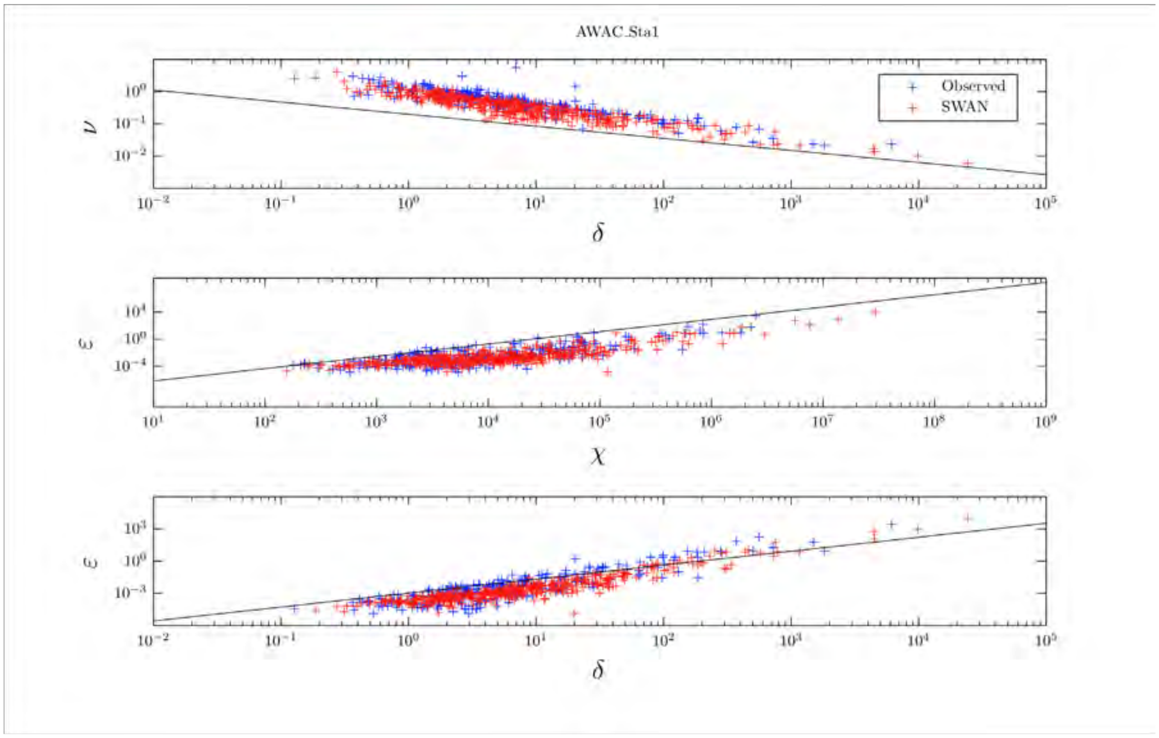



***Fig. 4: Comparison of computed and observed non-dimensional wave energy and frequency at AWAC STA1 with empirical formulation of Young and Verhagen, 1996 included for reference (black line). Upper panel: frequency as a function of depth. Middle panel: energy as a function of fetch. Bottom panel: energy vs. depth. Fetch calculation includes water level, direction, and position of the observation (Fig 2).***

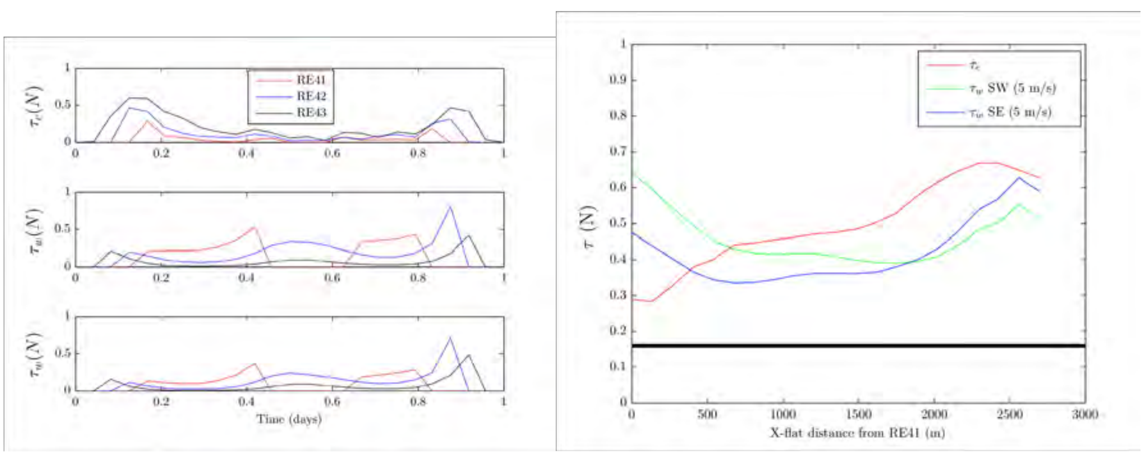



***Fig. 5: [Left] Bed stress over a spring tidal cycle at three cross flat locations. Upper panel: stress due to currents. Middle panel: wave-induced stress driven by SW winds at 5 m/s. Lower panel: wave-induced stress driven by SE winds at 5 m/s. [Right] Cross-flat profile of maximum bed stress over a spring-neap cycle. Critical shear stress of dominant grain size on the Skagit flats (phi=2.5) shown for reference (black line).***

**2. Erosion Potential**
In the present work, the wave model is run in offline mode. Calculation of bed stresses including nonlinear wave-current interaction are computed using the method of Soulsby. Mean bed stresses over the wave orbital period are used to set the boundary condition for the momentum equations. Maximum stresses are used to compute the potential cumulative erosion (PCE) in meters. For measurements of cumulative erosion, sediment parameters based on a single sediment of fine sand (phi = 2.5). This is a representative grain size for the Skagit Flats (provided by Kristen Lee, UW)

$$PCE = \sum \frac{\Delta t}{\rho_{sed}} E\left(\frac{kg}{m^2 s}\right) MAX\left[\left(\frac{\tau_{cw\max}}{\tau_{crit}} - 1\right), 0\right]$$

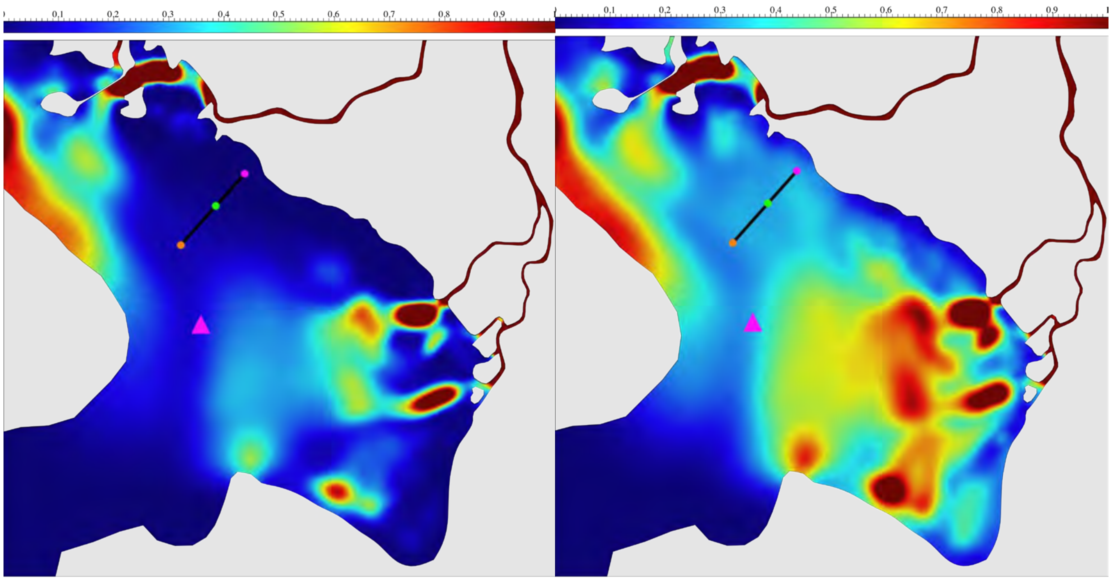



***Fig. 6: Model-computed cumulative erosion in meters for the Skagit Flats for the period June 1, 2009 through Sep 1, 2009. Left panel: Currents only. Right panel: Currents and Waves***

**IMPACT/APPLICATIONS**

A key outcome of this work is the development of a coupled wave-current-sediment model for the study of tidal flats. The work will include an evaluation of numerical approaches, including the flux discretization of the wave action in geographic space, the implementation of the radiation stress terms, and the techniques for applying the coupled model over an extensive intertidal zone. Validation efforts will draw on the intensive observation program supported by this DRI and will help to make conclusions about the potential of such a model as well as define future research needs in terms of development or need for additional data. By including the dominant processes controlling the sediment fluxes on the flats, the model will enable significant study of the contributions of individual processes as well as contributions from interactions of processes.

## RELATED PROJECTS

In this work we work closely with other investigators participating in the ONR tidal flats DRI. The key collaborators are C. Sherwood and R. Signell (USGS, Woods Hole) who will be assisting with the development, implementation, and validation of CSTMS within FVCOM as well as processing of bathymetry for the model domain. We are also working closely with D. Ralston (WHOI) in the model development and validation.

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